

The Quintom Model of Dark Energy

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Abstract

In this paper I give a brief review on the recently proposed new scenario of dark energy model dubbed *Quintom*. Quintom describes the dynamical dark energy models where the equation of state getting across the cosmological constant boundary during evolutions. I discuss some aspects on the quintom model buildings and the observational consequences.

1 Introduction

The nature of dark energy is among the biggest problems in modern physics and has been studied widely. The simplest candidate of dark energy is the cosmological constant, it suffers from the well-known fine-tuning and coincidence problems [1, 2]. Alternatively, dynamical dark energy models with the rolling scalar fields have also been proposed, such as quintessence[3, 4], the ghost field of phantom [5] and the model of k-essence which has non-canonical kinetic term [6].

Given that currently we know very little on the theoretical aspects of dark energy, the cosmological observations play a crucial role in our understandings. The model of phantom has been proposed in history due to the fact that the observations have shown some mild preference for an equation of state(EOS) smaller than -1 [5]. Although in this scenario dark energy violates the weak energy condition(WEC) and leads to the problem of quantum instabilities[7, 8], we need more efforts on this observation-inspired topic.

The Type Ia supernova (SNIa) observations from the HST/GOODS program and the previous supernova data[9], which make the only direct measurements of dark energy, somewhat favor the dynamical dark energy model with an equation of state getting across -1 during the evolutions[10]. If such a kind of dynamical dark energy were verified by future observations, it would be a challenge to the dark energy model buildings. Neither the cosmological constant nor the dynamical scalar fields like quintessence or phantom would be the source driving the current accelerated expansion of the Universe. The model of quintessence has an equation of state which is always no smaller than minus unity while the ghost field of phantom has an EOS always no larger than -1 . Basing on these facts we proposed a new model of dark energy dubbed *Quintom*[11], in the sense that the required behavior of the dynamical dark energy combines that of quintessence and phantom. The purpose of this paper is to discuss briefly some aspects on the quintom model buildings and the corresponding observational consequences.

2 The Quintom Model of Dark Energy

Phenomenologically in comparison with quintessence and phantom, the behavior of quintom is more flexible and it can lead to some distinctive pictures in the determinations in the future of our Universe. In Ref.[12] we proposed a scenario of quintom with oscillating equation of state. We find oscillating Quintom can unify the early inflation and current acceleration of the universe, leading to oscillations of the Hubble constant and a recurring universe. Our oscillating Quintom would not lead to a big crunch nor big rip. In Ref.[13] we found interestingly the current observations somewhat favor an oscillating quintom with a much smaller period than that required in the recurrent universe scenario. Note in Refs.[12, 13] they are phenomenological studies only and are not focused on quintom model buildings.

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At the first sight it seems to be easy for the quintom model buildings, since naively one may consider a model with a non-canonical kinetic term with the following effective Lagrangian[11]:

$$\mathcal{L} = \frac{1}{2}f(T)\partial_\mu Q\partial^\mu Q - V(Q) , \quad (1)$$

where $f(T)$ can be a dimensionless function of the temperature or scalar fields. During the evolution of the universe when $f(T)$ crosses the point of zero it gives rise to the crossing of the cosmological constant boundary. However one also needs to consider the dynamics of the $f(T)$ term in reality and this makes it not straightforward for successful quintom model buildings. When we consider realistic quintom models we need also to consider their spatial fluctuations. It is crucial for us to understand its imprints in the cosmological observations. If we simply neglect dark energy perturbations and start from parametrizations of the scale factor $a(t)$, it would be very easy to construct quintom models since this is somewhat like reconstruction of a using $w(t)$.

It turns out that if we consider the usual kessence as the candidate of quintom, at the crossing point it cannot be quantized in a canonical way[15]. Due to the problems on perturbations, we cannot realize quintom with a single fluid or single scalar field in the conventional way. In general one needs to add extra degrees of freedom for successful quintom model buildings. In Ref[11] we considered the simplest case with one quintessence field and the other being the phantom field:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - \frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - V_0[\exp(-\frac{\lambda}{m_p}\phi_1) + \exp(-\frac{\lambda}{m_p}\phi_2)] .$$

Such a two-field model can easily cross the cosmological constant boundary(See also [14]). However for the simplest two-field model we are faced with the problem of ghost instabilities inherited inevitably in the phantom component[7, 8]. Another possibility of introducing the extra degrees of freedom for the realization of quintom was proposed in Ref. [16], where we introduced higher derivative operators to the Lagrangian. Specifically we considered a model with the Lagrangian

$$\mathcal{L} = -\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi + \frac{c}{2M^2}\square\phi\square\phi - V(\phi) , \quad (2)$$

where $\square \equiv \nabla_\mu\nabla^\mu$ is the d'Alembertian operator. The term related to the d'Alembertian operator is absent in the quintessence, phantom and the k-essence model, which is the key to make the model possible for w to cross over -1 . We have shown in [16] this Lagrangian is equivalent to an effective two-field model

$$\mathcal{L} = -\frac{1}{2}\nabla_\mu\psi\nabla^\mu\psi + \frac{1}{2}\nabla_\mu\chi\nabla^\mu\chi - V(\psi - \chi) - \frac{M^2}{2c}\chi^2 , \quad (3)$$

with

$$\chi \equiv \frac{c}{M^2}\square\phi , \quad (4)$$

$$\psi \equiv \phi + \chi . \quad (5)$$

Note that the redefined fields ψ and χ have opposite signs in their kinetic terms. One might be able to derive the higher derivative terms in the effective Lagrangian (2) from fundamental theories. For example it has been shown that this type of operators appears as some quantum corrections or due to the non-local physics in the string theory. In principle as the Lagrangian (2) is equivalent to the two-field model the phantom instabilities still exist. However we can also expect in the two cases their behaviors are different when we consider the possible interactions. In particular, Ref.[18] has shown that in this scenario ghosts arise because of the canonical treatment, where ϕ and $\square\phi$ are regarded as two independent variables. An alternative quantization based on the path integral seems to be intriguing towards solving the problem of ghosts[18].

The model of quintom was initiated by the SNIa observations, in realistic quintom model buildings we need to consider the imprints in the concordance observational cosmology. In the probe of quintom signatures in cosmic microwave background (CMB) and large scale structure (LSS) we need to consider the effects of dark energy perturbations. When dark energy is not simply the cosmological constant in

general it will cluster on the largest scales, which can leave some imprints on the observations. Ref.[19] has shown that for scalar models of dark energy like quintessence and phantom, the effects of dark energy perturbations are to introduce more degeneracies with the equation of state on CMB. In our simplest two-field quintom case we have found that crossing the cosmological constant boundary would not lead to distinctive effects. On the other hand for models of scalar dynamical dark energy the equation of state is not a constant in general, however the effect on CMB can be almost identically described by a constant EOS:

$$w_{eff} \equiv \frac{\int da \Omega(a) w(a)}{\int da \Omega(a)} , \quad (6)$$

hence it is easily understood when we include the effects of quintom perturbations it will be in more degeneracy with the geometric parameter w . In general when we add geometrical data the degeneracy between a constant w_{eff} and a dynamical w can be somewhat broken, but it still exists due to limits on the precisions of the current SNIa observations.

In the study of quintom perturbations it is straightforward in the two-field case. But cosmologists are sometimes more interested in the inverse study on dark energy through fittings to the cosmological observations. In the fittings one typically parameterizes the equation of state. However when we parameterize quintom-like dark energy the problem arises in the study on the imprints of perturbations. We need to bear in mind what spectrum this kind of dark energy displays: it cannot be a simple one-field scalar or single ideal fluid, the perturbations will diverge for these cases. We introduce a small positive constant c to divide the whole region of the allowed value of the EOS w into three parts[15]: 1) $w > -1 + c$; 2) $-1 + c > w > -1 - c$; and 3) $w < -1 - c$. In Regions 1) and 3) the parameterized dark energy can be described as conventional quintessence and phantom. In Region 2) numerically we have set the derivatives of pressure and density perturbations to be zero at the extremely limited matching point. Through this method our study of parameterized quintom can resemble two-field quintom models and no singularities appear. In Ref.[17] we have made global fittings on the current status of dynamical dark energy including quintessence, phantom and quintom. We have found that a dynamical dark energy with the EOS getting across -1 is favored at 1σ with the combined constraints from WMAP, SDSS and the "gold" dataset of SNIa by Riess *et al*, see Fig.1. In previous investigations due to the problems on quintom perturbations the fittings in the literature typically did not include dark energy perturbations in the probe of dynamical dark energy. We can find this will lead to nontrivial bias. Similarly we can also easily understand quintom perturbation will play a significant role in probing dynamical dark energy using future precise measurements like SNAP and JDEM.

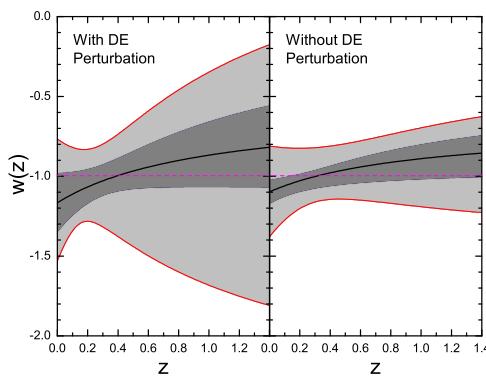


Figure 1: Constraints on $w(z)$ using WMAP + 157 "gold" SNIa data + SDSS with/without DE perturbation[17]. Median(central line), 68%(inner, dark grey) and 95%(outer, light grey) intervals of $w(z)$ using 2 parameter expansion of the EOS: $w(z) = w_0 + w_1 \frac{z}{1+z}$, with z being the redshift.

We should point out currently on the observational aspect a cosmological constant still fits the data quite well. Nevertheless the SNIa observations, which make the only direct detections of dark energy,

somewhat favor a dynamical quintom-like dark energy. Note we need to set several priors before we can get detailed investigations on probing dark energy with SNIa only. On the other we need more thorough understandings on the dynamical mechanism of Type Ia supernova, both the quality and quantity of SNIa are to be improved. Currently there are still various possibilities and alternatives on the model of dark energy[20].

Both theoretical and observational probe of dark energy need still go a long way. If we start always from a Λ CDM model in the probe of our universe we cannot achieve more subtle physics beyond that. This is necessary to bear in mind for us to understand the nature of dark energy with the accumulation of the observational data.

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